Relative contribution ratios of skin and proprioceptive sensations in perception of force applied to fingertip

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Abstract—Humans perceive a force applied to their fingertips by integrating skin and proprioceptive sensations. In this study, we investigated the relative contribution ratios of these sensations using two approaches. Decoupled forces were applied to the finger pad and proximal interphalangeal joint of the index finger of the participants. First, we calculated the ratios from the point of subjective equality between the skin and the proprioceptive perceptions. Second, we obtained discrimination limens of the two perceptions to compute their contribution ratios. The results of these two approaches showed good agreement. Additionally, we investigated how the magnitudes of forces, which were 1.0 and 0.3 N, applied to a fingertip affect the relative contribution ratios of the two sensory channels. When humans perceived the force of 1.0 N, the relative contribution ratios of skin and proprioceptive sensations were 16–28% and 72–84%, respectively. In contrast, when humans perceived the force of 0.3 N, the relative contribution ratios were 37–55% and 45–63%, respectively. These relative contribution ratios can be utilized for the design of efficient haptic interfaces.

Index Terms—Skin stretch, Sensory integration, Force perception.

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1 INTRODUCTION

Humans integrate both skin and proprioceptive sensations to estimate the properties of an object while exploring it with their fingers. For example, these two sensations provide information about the weight [1], [2], [3], hardness [4], [5], and length [6] of the object. Furthermore, links between these two sensations have been suggested to play a role in the perception of the surface shape [7], [8]. Knowledge of the relative contribution ratios of skin and proprioceptive sensations is of great importance. Such knowledge should lead to not only the clarification of the perceptual mechanism but also the development of haptic displays. For example, an interface that applies shear deformation to the finger pad can impart sensations of force and weight as an alternative to a kinesthetic sense display. Provancher and Sylvester demonstrated that a force and shear deformation imparted to the human fingertip affect the human estimation of friction [9]. The design guidelines or implementation for such a display were presented [10], [11]. Kurita et al. developed an interface that presented the weight and friction coefficient of grasped objects by controlling the shear deformation of the human finger pad [12]. Minamizawa et al. demonstrated that shear and normal force feedback to finger pads by wearable haptic interfaces provided a good approximation of the haptic interaction with virtual objects [13]. Similar effects can be expected only by the application of normal or rotational forces to finger pads [14], [15]. Feeding back a shear force to the finger pad potentially improves the performance of a task involving manipulation of an object in the virtual space [16]. As shown in such interfaces, the application of one or both of the forces and shear deformation to the finger pad is effective in designing haptic interfaces. Forces applied to the finger pads should be manipulated as precisely as those applied to the hands because studies in the field of psychophysics suggest that humans can accurately estimate the force applied to the finger pad [17].

Despite the wide use of force feedback to finger pads, the relative contribution ratios of the two sensory channels when a force is applied to a fingertip have not yet been studied in adequate detail. Provancher and Sylvester focused on the relationship between the skin deformation and the friction stimuli applied to the fingertip [9]. Minamizawa et al. [13] and Giachritsis et al. [3]

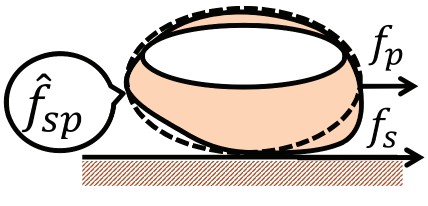

Fig. 1. Integration of perceived force. The proprioceptive force (f_p) and the finger pad force (f_s) are decoupled, and the perceived force ($\hat{f}_{sp}$) is the integration of these two forces.

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investigated the roles of skin and proprioceptive cues in the weight perception of an object gripped by the thumb and the index finger. These studies did not directly discuss the contribution ratios of the cues, or they addressed the weight perception via a two-fingered grip under which the roles of skin sensations tend to be greater in the force perception (see also the first paragraph of sec. 5.1). In addition, active and passive grip conditions were mixed in some cases. We investigate the contribution ratios for one finger, which is a more general condition. Furthermore, we adopt two approaches–a point of subjective equality (PSE) approach and one based on the discrimination limen (DL)–for investigating the contribution ratios of the two perceptual cues in order to obtain more reliable conclusions.

The objective of this study is to examine the relative contribution ratios of skin and proprioceptive sensations in the perception of a force applied to a fingertip. Humans apply an equal-sized force to the finger pad and the entire finger when they manipulate objects. In this study, the two sensations were decoupled. As shown in Fig. 1, the two sensations were independently imparted by the skin (shear deformation to the finger pad) and the proprioceptive (force on muscles and tendons of finger) stimuli although some interference with each cue existed. First, we obtain the relative contribution ratios by identifying the PSE of the stimuli. Second, we specify the DLs of the two sensations and then calculate the ratios of the sensory channels. Additionally, we investigate how the magnitudes of forces (1.0 N and 0.3 N) applied to a fingertip affect the relative contribution ratios of the two sensory channels. Generally, as the force applied to the fingertip decreases, the skin sensation becomes more dominant [18]. All experimental procedures were admitted by the ethical committee of the Graduate School of Engineering at Nagoya University.

2 TWO APPROACHES FOR RESOLUTION OF RELATIVE CONTRIBUTION RATIOS

2.1 Approach based on point of subjective equality

Under the assumption of a linear cue combination, the integrated force perception $\hat{f}_{sp}$ is given by

$$\hat{f}_{sp} = w_{s1}(\hat{f}_s, \hat{f}_p)\hat{f}_s + w_{p1}(\hat{f}_s, \hat{f}_p)\hat{f}_p, \tag{1}$$

where $\hat{f}_s$ and $\hat{f}_p$ are the perceived forces applied to the skin and proprioceptive cues, respectively, and w_{s1} and w_{p1} are the relative weights when $\hat{f}_s$ and $\hat{f}_p$ are integrated [19]. As previously described, these weights depend on the force applied to the fingertip. Additionally, w_{s1} and w_{p1} are related by $w_{s1} + w_{p1} = 1$. Two subjectively equivalent stimuli are described by

$$\begin{aligned} &w_{s1}(\hat{f}_{s1}, \hat{f}_{p1})\hat{f}_{s1} + w_{p1}(\hat{f}_{s1}, \hat{f}_{p1})\hat{f}_{p1} \\ &= w_{s1}(\hat{f}_{s2}, \hat{f}_{p2})\hat{f}_{s2} + w_{p1}(\hat{f}_{s2}, \hat{f}_{p2})\hat{f}_{p2}. \end{aligned} \tag{2}$$

When $\hat{f}_s$ and $\hat{f}_p$ values are close, respectively, we can approximate that $w_{s1}(\hat{f}_{s1}, \hat{f}_{p1}) = w_{s1}(\hat{f}_{s2}, \hat{f}_{p2})$ and $w_{p1}(\hat{f}_{s1}, \hat{f}_{p1}) = w_{p1}(\hat{f}_{s2}, \hat{f}_{p2})$. This equation, then, can be rewritten as

$$w_{s1}(\hat{f}_{s1}, \hat{f}_{p1})\Delta\hat{f}_s + w_{p1}(\hat{f}_{s1}, \hat{f}_{p1})\Delta\hat{f}_p = 0, \tag{3}$$

where $\Delta\hat{f}_s = \hat{f}_{s1} - \hat{f}_{s2}$ and $\Delta\hat{f}_p = \hat{f}_{p1} - \hat{f}_{p2}$. Based on the relationship $w_{s1} + w_{p1} = 1$ and (3), the relative contribution ratios for the skin and proprioceptive sensations are given by

$$w_{s1}(\hat{f}_{s1}, \hat{f}_{p1}) = \frac{\Delta f_p}{\Delta f_p - \Delta f_s}, \tag{4}$$

$$w_{p1}(\hat{f}_{s1}, \hat{f}_{p1}) = 1 - w_{s1}(\hat{f}_{s1}, \hat{f}_{p1}). \tag{5}$$

2.2 Approach based on discrimination limen

A representative DL-based approach is the maximum likelihood estimation (MLE) or the minimum variance estimation (MVE) model that determines the contribution ratios based on the variance of perception [19], [20]. By definition, the minimization of variance maximizes the reliability of the integrated information.

When the DL of one cue is measured, potentially related cues are preferably kept useless [20], [21], [22]. In the case of our study, such a channel can be created using uncorrelated noisy vibratory forces. However, such noise signals to the proprioceptive sensations significantly influence the skin sensations. Similarly, it is difficult to apply a force to a finger pad without influencing the other skin parts. It is challenging to entirely segregate the skin and the proprioceptive perceptions. Therefore, in the present study, where cue isolation is difficult, one cue is fixed whereas another cue is varied. For such cases [20], the integrated percepts are

$$\hat{f}_{sp1} = w_{s2}(\hat{f}_{s1}, \hat{f}_{p1})\hat{f}_{s1} + w_{p2}(\hat{f}_{s1}, \hat{f}_{p1})\hat{f}_{p1} \tag{6}$$

$$\hat{f}_{sp2} = w_{s2}(\hat{f}_{s2}, \hat{f}_{p1})\hat{f}_{s2} + w_{p2}(\hat{f}_{s2}, \hat{f}_{p1})\hat{f}_{p1} \tag{7}$$

with fixed $\hat{f}_{p1}$. When $\hat{f}_{s1}$ is close to $\hat{f}_{s2}$, it is approximated that $w_{s2}(\hat{f}_{s1}, \hat{f}_{p1}) = w_{s2}(\hat{f}_{s2}, \hat{f}_{p1})$ and $w_{p2}(\hat{f}_{s1}, \hat{f}_{p1}) = w_{p2}(\hat{f}_{s2}, \hat{f}_{p1})$. Subtracting (7) from (6) gives

$$\hat{\sigma}_{sp} = w_{s2}(\hat{f}_{s1}, \hat{f}_{p1})\hat{\sigma}_s, \tag{8}$$

where $\hat{\sigma}_{sp} = \hat{f}_{sp1} - \hat{f}_{sp2}$ and $\hat{\sigma}_s = \hat{f}_{s1} - \hat{f}_{s2}$. Similarly,

$$\hat{\sigma}_{sp} = w_{p2}(\hat{f}_{s1}, \hat{f}_{p1})\hat{\sigma}_p \tag{9}$$

holds. Let $\hat{\sigma}_s$ and $\hat{\sigma}_p$ be the respective deviations of percepts f_s and f_p when one cue is manipulated and the other is fixed. When the two cues are optimally integrated, $\hat{\sigma}_{sp}$ becomes equal to the deviation of $\hat{f}_{sp}$. From (8), (9), and $w_{s2} + w_{p2} = 1$, the relative contribution ratios of the two sensory channels are described by

$$w_{s2}(\hat{f}_{s1}, \hat{f}_{p1}) = \frac{\hat{\sigma}_p}{\hat{\sigma}_s + \hat{\sigma}_p}, \tag{10}$$

$$w_{p2}(\hat{f}_{s1}, \hat{f}_{p1}) = 1 - w_{s2}(\hat{f}_{s1}, \hat{f}_{p1}). \tag{11}$$

3 EXPERIMENT

3.1 Method

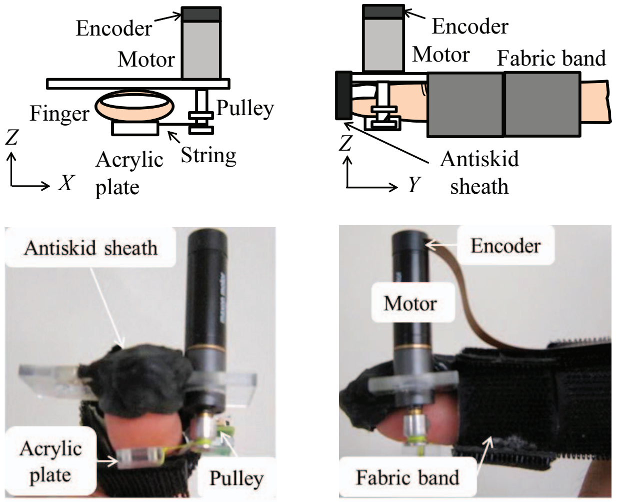
3.1.1 Experimental System

The requirements for the force and tactile interfaces used in the experiment are that the displays can separately apply forces to the skin and the proprioceptive stimuli. For the skin stimulus, the display applied a shear force to the finger pad, f_s. For the proprioceptive stimulus, the display applied a force to the proximal interphalangeal joint of the finger, f_p.

Fig. 2 shows the tactile interface developed for the skin stimulus to the finger pad. The interface used an acrylic plate that was placed beneath the finger pad and was driven by a DC motor (RE-10, Maxon motor, Sachseln, Switzerland) to which a string was fastened. The acrylic plate and the finger pad were bonded by a double-sided tape for preventing slippage. The finger pad was fixed in place by the antiskid sheath of the interface, which precluded the force applied to the skin from being transferred to the finger joint. However, this also means that the reaction force was received by the nail part. The motor was torque-controlled using a motor driver (ADS 50/5, Maxon motor) while compensating for the preliminary identified gear friction.

Fig. 3 shows the interface for applying the proprioceptive force to the finger. By using a set of idlers and string, the interface transferred the force to the fabric band twisted around the proximal interphalangeal joint of the finger. One of the idlers was linked to a spring tensioner. The force was generated by a DC motor (RE-280, Mabuchi Motor Co. Ltd., Japan) to which a string was fastened. As well as the device for the finger pad, the torque of the motor was controlled by a motor driver. The torque instruction was determined such that the preliminary identified friction caused by a gear and pulley mechanism was compensated for. The force is mainly perceived by the metacarpal phalangeal joint of the finger and the wrist. It should be noted that when the interface applied the force to the fabric band, a subtle pressure stimulus was also applied to the lateral side of the finger in contact with the fabric band. It is difficult to transfer the force to the muscle and tendon without also stimulating the skin unless we locally anesthetize a digit. Such solutions were seen in some studies to test the role of cutaneous sensations [23], [24], [25], [26]. For ethical matters to use anesthesia for non-medical purposes, we avoided this approach.

As shown in Fig. 4, participants wore both displays on the right index finger with their forearms resting on an armrest. Beneath the acrylic plate of the skin stimulator, a low-friction linear slider was located so that the plate beneath the finger pad could be moved without the frictional constraint with the floor surface. Furthermore, two load cells (Model 1004, Tedea-Huntleigh, Canada, resolution: 1.0×10^{-4} N) measured the finger's pressing force along the Z-axis for controlling the experimental conditions (see also sec. 3.1.2).



(i) Front view (ii) Side view

Fig. 2. Interface for applying shear force to finger pad

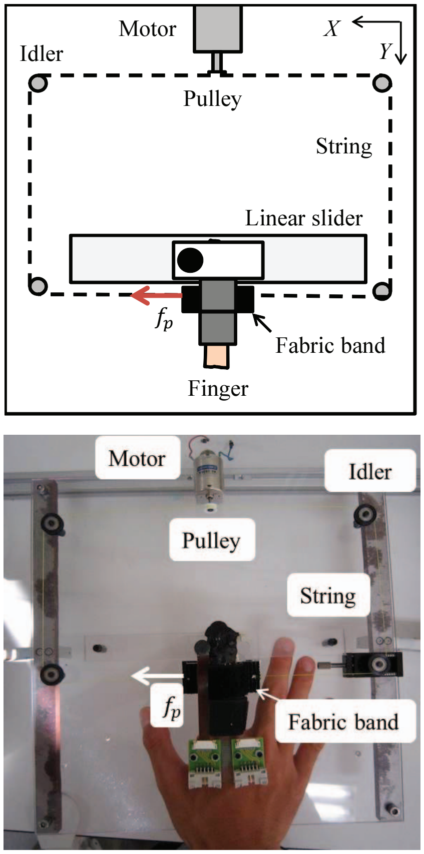


Fig. 3. Interface for applying proprioceptive force to finger

3.1.2 Task and participants

The experiment was conducted based on the method of constant stimuli. First, the interface applied either the reference or the test stimulus to the participants' finger for 2 s. Second, the other stimulus was applied for 2 s. Afterward, participants were asked to judge the forces with which the interfaces pulled the finger and answer whether they perceived the force of the second

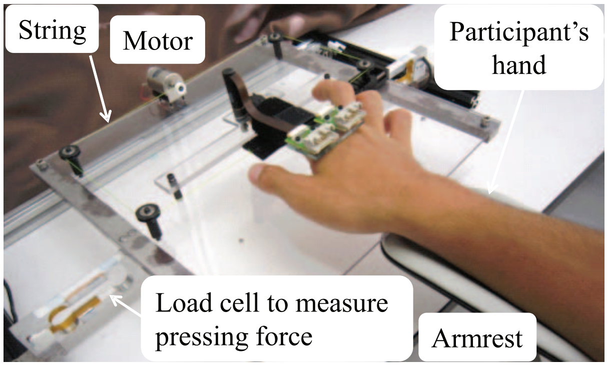


Fig. 4. Experimental setup: Participant wearing skin and proprioceptive force displays

stimulus to be larger than that of the first stimulus. They were instructed to maintain a constant finger position and pressing force at 1–2 N during each trial, and they could see this force value displayed on a screen before each trial. It is known that the impedance of the finger pad varies with the pressing forces [27], [28]. They closed their eyes so as not to see their fingers and aurally blocked the motor activation sound by listening to pink noise through headphones. The participants (P1–P8) were eight students recruited from Nagoya University. All of them were ignorant of the objective of the experiment.

3.1.3 Stimuli

The skin sense display applied a shear force f_s to the finger of the participant. Simultaneously, the proprioceptive display applied force f_p to the proximal interphalangeal joint of the finger. The reference stimuli were (f_{rs}, f_{rp}) = (1.0 N, 1.0 N) and (0.3 N, 0.3 N). The following test stimuli were presented.

Test stimuli for estimating PSE: The test stimuli for 1.0 N were (f_{ts}, f_{tp}) = (0.7 N, {0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3 N}) or (1.3 N, {0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3 N}). The test stimuli for 0.3 N were (f_{ts}, f_{tp})=(0.2 N, {0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 N}) or (0.4 N, {0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6 N}). We investigated the PSE of the reference stimulus using these test stimuli.

Test stimuli for estimating DL: The test stimuli for 1.0 N were (f_{ts}, f_{tp}) = ({0.4, 0.6, 0.8, 1.2, 1.4, 1.6 N}, 1.0 N) or (f_{ts}, f_{tp}) = (1.0 N, {0.7, 0.8, 0.9, 1.1, 1.2, 1.3 N}). The test stimuli for 0.3 N were (f_{ts}, f_{tp}) = ({0.0, 0.1, 0.2, 0.4, 0.5, 0.6 N}, 0.3 N) or (f_{ts}, f_{tp}) = (0.3 N, {0.0, 0.1, 0.2, 0.4, 0.5, 0.6 N}). The step size of the test stimuli was set so that participants could easily distinguish the maximum and the minimum stimuli from the reference stimuli. The skin sensation has inferior discriminability around 1.0 N compared to the proprioception. Hence, the step size for f_{ts} was set to 0.2 N around 1.0 N.

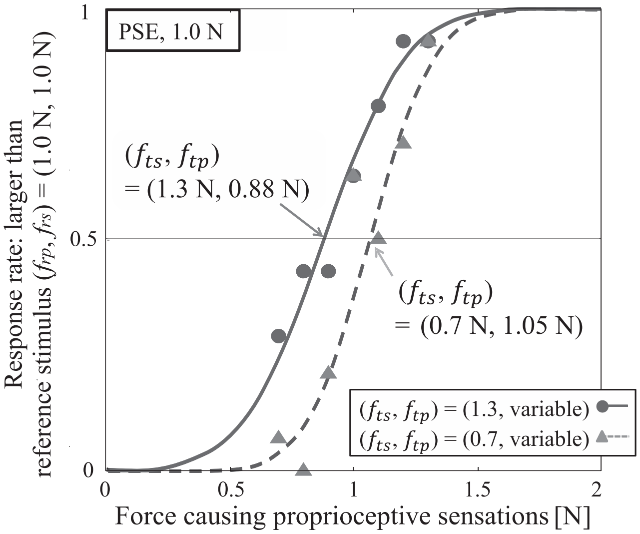


Fig. 5. Example data to obtain point of subjective equality from a single participant (P7). Response rates and fitting curves of "bigger" toward reference stimulus of (f_{rs}, f_{rp}) = (1.0 N, 1.0 N). Circles and triangles indicate response rates of test stimuli at $f_s = 1.3$ and $f_s = 0.7$, and they are fitted to solid and dashed curves, respectively.

The order of the test stimuli was determined by a pseudo-random generator in a single set consisting of 52 types of stimuli. Fourteen sets were conducted, which means that each stimulus was presented 14 times through the experiment. Thus, in total, 728 (52 stimuli × 14 repetition) trials were conducted for each individual. Different orders were used for different participants. The participants took a 5-min rest every 50 trials. The entire procedure took 6–7 h per participant, including the necessary explanations, practice, and documentation.

3.1.4 Fitting of normal distribution curve

The response variable was the proportion of responses for which participants answered that the force of the test stimulus was larger than that of the reference stimulus. Using MLE fitting [29], the response rates were fitted with a cumulative density function of the normal distribution. We defined f_{tp} or f_{ts} at which the rate of the fitted curve is 0.5 as the PSE. The 84% DL was defined as the difference of the forces between response rates of 0.84 and 0.50.

3.2 Results

3.2.1 Results of PSE-based approach

Fig. 5 shows the example data for 1.0 N from a single participant (P7). For the test stimuli at $f_{ts} = 0.7$ and 1.3 N, the PSEs were (f_{ts}, f_{tp}) = (0.7, 1.05) and (1.3, 0.88), respectively. The relative contribution ratios were calculated using (2)–(5) for individuals. Table 1 shows Δf_p, contribution ratios reported by the participants, mean and standard deviation of these values, and χ^2 for fitting. If these values had exceeded $\chi^2(0.95, 6) = 12.6$, the fitting would not have been statistically valid. Δf_p, w_{p1}, and w_{s1} are the average values for the two PSEs of $f_{ts} = 0.7$ N and $f_{ts} = 1.3$ N. The results for 1.0 N showed that the contributions used for combining the

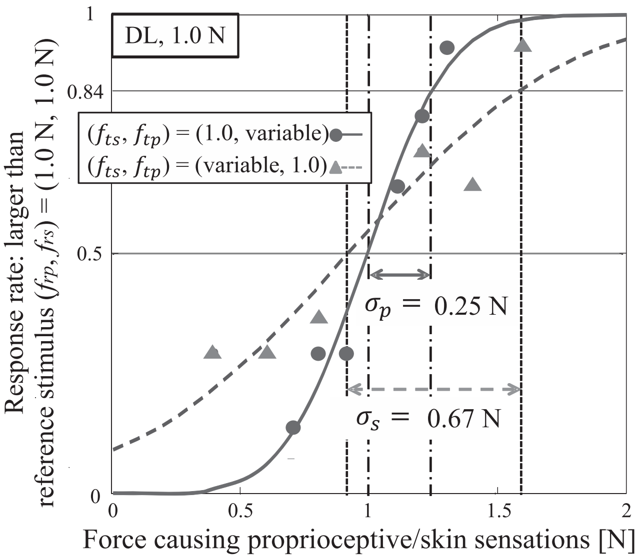


Fig. 6. Example data to obtain DL from a single participant (P7). Response rates and fitting curves of "bigger" toward reference stimulus of $(f_{rs},\ f_{rp})$ = (1.0 N, 1.0 N). Circles and triangles indicate response rates of test stimuli when f_p and f_s are variable, and they are fitted to solid and dashed curves, respectively.

two forces were 21% skin and 79% proprioception on average. Similarly, Table 2 shows the results for 0.3 N. Δf_p, w_{p1}, and w_{s1} are the average values for the PSEs of $f_{ts} = 0.2$ N and $f_{ts} = 0.4$ N. The results showed that the average contribution ratios were 46% skin and 54% proprioception for the reference force of 0.3 N.

3.2.2 *Results of DL-based approach*

Fig. 6 shows the example data for 1.0 N from P7. When f_{tp} and f_{ts} of the test stimuli were variable values, the 84% DL values of this participant were 0.25 and 0.67 N for proprioceptive and skin sensations, respectively. We calculated the 84% DL for all participants, however, P3 was removed from the statistics owing to this large χ^2 where the confidence limit was $\chi^2(0.95, 5) = 11.1$. We then obtained the contribution ratios by using (10) and (11). Table 3 shows 84% DL, contribution ratios reported by the participants, mean and standard deviation of these values, and χ^2 for fitting. The results showed that the average ratios of the weights used for combining the two forces were 23% skin and 77% proprioception. The average PSEs of the reference stimuli were 1.01 ± 0.05 N and 1.04 ± 0.11 N for the constant f_{ts} and f_{tp} conditions, respectively, and they indicated that the participants were not significantly biased.

We also calculated the 84% DL of skin and proprioceptive sensations for 0.3 N. For the same reason as above, P1 was removed from the statistics. Table 4 shows the statistic variables for individuals and their mean and standard deviations. The results showed that the mean weights were 51% skin and 49% proprioception. The average PSEs of the reference stimuli were 0.27 ± 0.04 N and 0.26 ± 0.05 N, for the constant f_{tp} and f_{ts} conditions, respectively. These values were fairly close to the value of the reference stimulus, i.e., 0.3 N.

4 EXPERIMENT TO TEST VALIDITY OF DL-BASED APPROACH

When $\hat{f}_s$ and $\hat{f}_p$ are perceptually integrated following the model described in sec. 2.2 with both cues being taken into account by the observer and weighted in an optimal fashion, the DL for the integrated skin and proprioceptive sensations is estimated by

$$\hat{\sigma}_{sp} = \frac{\hat{\sigma}_s \hat{\sigma}_p}{\hat{\sigma}_s + \hat{\sigma}_p}. \tag{12}$$

The results of DL-based approaches can be experimentally validated by comparing the value of $\hat{\sigma}_{sp}$ estimated by (12) and that obtained directly from an experiment.

4.1 Stimuli and Task

We investigated the DL values for 1.0 N when the force stimuli for the two sensations were consistently changed. Five of the eight participants took part in this experiment after participating in the experiments described in the previous section. The other three participants could not participate in this experiment owing to the limitations imposed by their work schedules. The employment of another group of participants might have led to more reliable conclusions, however, due to an economic reason, we asked the same participants to join this experiment. As in the previous tasks, they performed a task in which they compared the forces between the reference and the test stimuli. The reference stimulus was $(f_{rs},\ f_{rp})$ = (1.0 N, 1.0 N), and the test stimuli were $f_{ts} = \{0.7,\ 0.8,\ 0.9,\ 1.1,\ 1.2,\ 1.3\}$ N, where $f_{tp} = f_{ts}$. These six types of stimuli were presented in a random order with each one being repeated 10 times. In total, 60 trials were performed for individuals, and they took approximately 40–60 min.

4.2 Results

The results were analyzed as in the case of the previous experiments. All participants' results were well represented by cumulative Gaussian curves. The 84% DL forces for integrated skin and proprioceptive sensations were 0.19, 0.17, 0.09, 0.16, and 0.21 N for the five participants as summarized in Table 5. Their mean and standard deviations were 0.16 ± 0.04 N. The table also shows the DL values estimated by (12) from the seven participants. These values were calculated using their $\hat{\sigma}_p$ and $\hat{\sigma}_s$ values, as listed in Table 3, that were obtained through the experiments described in the previous section. The estimated and observed values are consistent ($t_0(10) = 0.14$, $p = 0.89$, two-tailed unpaired t-test, $1 - \beta = 0.99$ with the possible effect of 0.1 N). This indicates that the DL-based approach was potentially valid for 1.0 N. Although we could not conduct the same

TABLE 1

Experimental results of PSE-based approach for 1.0 N. Δf_p corresponding to change in forces applied to finger pad (Δf_s = 0.30 N). Relative contribution ratios for skin (w_{s1}) and proprioceptive sensations (w_{p1}). χ^2 of fitting to normal cumulative density functions at $f_{ts} = 1.3$ N and $f_{ts} = 0.7$ N.

Participant	P1	P2	P3	P4	P5	P6	P7	P8	Ave. ± s.d.
Δf_p [N]	0.08	0.15	0.03	0.08	0.09	0.09	0.09	0.06	0.08 ± 0.03
w_{p1}	0.79	0.66	0.90	0.79	0.77	0.78	0.78	0.83	0.79 ± 0.07
w_{s1}	0.21	0.34	0.10	0.21	0.23	0.22	0.22	0.17	0.21 ± 0.07
$\chi^2\|_{f_{ts}=1.3}$	6.57	1.76	1.26	2.00	3.93	1.79	0.46	3.77	-
$\chi^2\|_{f_{ts}=0.7}$	10.3	5.35	1.99	5.23	2.77	1.49	4.17	0.40	-

TABLE 2

Experimental results of PSE-based approach for 0.3 N. χ^2 at $f_{ts} = 0.4$ N and $f_{ts} = 0.2$ N. Δf_p corresponding to Δf_s of 0.10 N.

Participant	P1	P2	P3	P4	P5	P6	P7	P8	Ave. ± s.d.
Δf_p [N]	0.05	0.16	0.09	0.09	0.20	0.06	0.04	0.08	0.10 ± 0.05
w_{p1}	0.66	0.39	0.54	0.52	0.34	0.64	0.69	0.55	0.54 ± 0.13
w_{s1}	0.34	0.61	0.46	0.48	0.66	0.36	0.31	0.45	0.46 ± 0.13
$\chi^2\|_{f_{ts}=0.4}$	2.20	0.25	4.65	2.34	1.35	1.92	1.43	4.89	-
$\chi^2\|_{f_{ts}=0.2}$	4.81	2.22	10.32	0.71	9.17	0.93	12.4	3.14	-

TABLE 3

Experimental results of DL-based approach for 1.0 N. χ^2 and 84% DL ($\hat{\sigma}$) for skin and proprioceptive sensations.

Participants	P1	P2	P3	P4	P5	P6	P7	P8	Ave. ± s.d.
$\hat{\sigma}_p$ [N]	0.27	0.21	0.18	0.19	0.26	0.24	0.25	0.13	0.22 ± 0.05
χ_p^2	1.51	1.13	0.52	0.37	2.87	1.06	0.49	0.89	-
$\hat{\sigma}_s$ [N]	0.69	0.58	-	0.84	0.59	0.89	0.67	1.20	0.78 ± 0.22
χ_s^2	1.97	0.50	16.0	5.46	0.20	1.03	0.94	0.82	-
w_{p2}	0.72	0.73	-	0.82	0.69	0.79	0.73	0.90	0.77 ± 0.07
w_{s2}	0.28	0.27	-	0.18	0.31	0.21	0.27	0.10	0.23 ± 0.07

TABLE 4

Experimental results of DL-based approach for 0.3 N.

Participants	P1	P2	P3	P4	P5	P6	P7	P8	Ave. ± s.d.
$\hat{\sigma}_p$ [N]	0.13	0.17	0.16	0.20	0.25	0.16	0.17	0.23	0.18 ± 0.04
χ_p^2	1.94	4.57	1.24	0.84	0.41	4.13	10.3	0.55	-
$\hat{\sigma}_s$ [N]	-	0.19	0.15	0.18	0.20	0.17	0.22	0.16	0.18 ± 0.02
χ_s^2	14.3	0.28	1.07	4.00	1.76	0.75	1.03	3.27	-
w_{p2}	-	0.53	0.49	0.47	0.45	0.52	0.57	0.41	0.49 ± 0.05
w_{s2}	-	0.47	0.51	0.53	0.55	0.48	0.43	0.59	0.51 ± 0.05

TABLE 5

Integrated cues' 84% DLs. Values estimated from the integration model and observed through experiments. χ^2 of fitting of the sampled data with normal cumulative density functions.

Participant	P1	P2	P4	P5	P6	P7	P8	Ave. ± s.d.
84%$\hat{\sigma}_{sp}$ [N] (estimated)	0.20	0.16	0.15	0.15	0.16	0.19	0.11	0.160 ± 0.03
84%$\hat{\sigma}_{sp}$ [N] (observed)	0.19	0.17	-	0.09	0.16	0.21	-	0.163 ± 0.04
χ_{sp}^2	6.42	1.13	-	0.13	2.32	1.96	-	-

test for the reference force of 0.3 N, it seems that there is no specific reason to dispute the validity of the DL-based approach for 0.3 N.

5 GENERAL DISCUSSION

5.1 Review of DLs in related studies

The DL of skin sensations in this study is 2–7 times larger than those in previous studies [3], [13], although it was not directly comparable owing to differences in conditions. In other words, the DL or contribution ratios of sensory cues vary with tasks. The earlier studies dealt with the weight perception of objects gripped by two fingers. In such cases, more skin cues are presumably available for humans than in the one-finger condition of the present study, whereas the wrist is commonly involved for both one- and two-fingered conditions. Furthermore, during the grip, the normal force to the finger pad varies with the shear force to it according to the nature of automatic grip force adjustment [24], [30].

Therefore, both the shear and the normal force cues applied to the fingertip affected the skin sensations whereas only the shear force was varied in the present study. Under such conditions, the DLs of previous studies are naturally lower than those of the present study because of the contributions of multiple cues [31].

The 84% DL of integrated cues in this study was 0.16 ± 0.04 N as reported in the previous section. This value corresponds to a 75% DL of 0.11 ± 0.02 N. Minamizawa et al. showed that the 75% DL for integrated skin and proprioceptive sensations under two-fingered grip was 9% for the standard stimulus of 1.0 N [13], which is close to our value of 11%. Furthermore, the Weber fraction of the perceived weight of a grasped object is around 10% [2], which is also similar to our value, although Giachritsis et al. reported a slightly lower value of 6% [3]. As to the one-fingered and active touch condition, the Weber fraction of the friction coefficients of smooth surfaces was reported to be 18% across wide range of friction coefficients (0.2–1.0) [32]. This and our values are reasonably close despite the difference of active and passive touch. Interestingly, the discriminability of forces applied to the fingertip worsens as the hand movements become more active [33]. Overall, the DLs estimated in the present study are likely to be consistent with those reported in earlier studies when both skin and proprioceptive cues are available.

5.2 Contribution ratios of skin and proprioceptive sensations

5.2.1 Ratios for perception of 1.0 N

From the PSE-based approach, in the perception of a force of 1.0 N to the human fingertip, the means and standard deviations of the contribution rates of the two sensory channels were

$$w_{s1,1.0} : w_{p1,1.0} = 0.21 \pm 0.07 : 0.79 \pm 0.07. \qquad (13)$$

From the DL-based approach, the contributions of the two sensory channels were

$$w_{s2,1.0} : w_{p2,1.0} = 0.23 \pm 0.07 : 0.77 \pm 0.07. \qquad (14)$$

These contribution ratios of skin sensation showed no statistically significant difference between the two approaches ($t_0(13) = 0.61$, $p = 0.60$, two-tailed unpaired t-test, $1 - \beta = 0.67$ with the possible effect of 0.1). The data for PSE- and DL-based approaches were based on eight and seven participants, respectively.

5.2.2 Ratios for perception of 0.3 N

From the PSE-based approach, in the perception of a force of 0.3 N, the relative contribution ratios of skin and proprioceptive sensations were

$$w_{s1,0.3} : w_{p1,0.3} = 0.46 \pm 0.13 : 0.54 \pm 0.13. \qquad (15)$$

From the DL-based approach, the contribution ratios were

$$w_{s2,0.3} : w_{p2,0.3} = 0.51 \pm 0.05 : 0.49 \pm 0.05. \qquad (16)$$

The values of these two approaches were in good agreement ($t_0(13) = 0.97$, $p = 0.35$, two-tailed unpaired t-test, $1 - \beta = 0.67$ with the possible effect of 0.1). The data for PSE- and DL-based approaches were based on eight and seven participants, respectively.

5.2.3 Contribution ratios estimated by two approaches

From the above analyses, the PSE and DL-based approaches show good agreement in terms of the estimated contribution ratios. Furthermore, the validity of the DL-based approach was confirmed in that the DL calculated from the model was not significantly different from that measured by a post-hoc experiment. These facts support the reliability of the experimental results despite the partly insufficient statistical powers of the above-described analyses.

As a conservative estimation of the contribution ratios, we calculated the 95% confidence intervals from the results. For a 1.0 N force applied to a fingertip, the intervals of skin contribution ratios were 21% ± 5% and 23% ± 5% for PSE and DL-based approaches, respectively. Hence, the superposed intervals of the skin ratio become 16–28%. The proprioceptive sensation ratio becomes 72–84%. Similarly, for a 0.3 N force, the skin ratios are 37–55% and the proprioceptive ratios are 45-63%.

6 CONCLUSION

In this study, we investigated the relative contribution ratios of skin and proprioceptive sensations in the perception of forces of 1.0 N and 0.3 N applied to the fingertip. We calculated the ratios using PSE- and DL-based approaches. The results of these approaches showed good agreement with each other. Moreover, the experimental- and literature-based inspection supported the validity of the results despite an imperfect experimental setup in which the two sensations could not be completely isolated. By superposing the 95% confidence interval of the contribution ratios from the two approaches, the ratios are summarized as follows for the experiments conducted in the present study. When humans perceive a force of 1.0 N, the relative contribution ratios of skin and proprioceptive sensations are 16–28% and 72–84%, respectively. In contrast, when humans perceive a force of 0.3 N, the respective ratios are 37–55% and 45–63%. Because skin is more sensitive than proprioception for the perception of relatively small forces applied to the finger pad, the contribution of skin increases as the applied force decreases.

Ideally, how these ratios vary with the applied forces should be further determined, as we dealt with only two force values. The roles of the two types of sensations can then be clarified, and this should provide design guidelines for haptic interfaces. Nonetheless, the findings of this study are quite noteworthy. For haptic interfaces with small force ranges, force feedback should be imparted to the finger pads, whereas finger pads can almost be neglected for large force ranges. For forces of around 0.3–1.0 N, both cues have to be considered. For example, a weight of 200–300 g feels lighter when proprioceptive cues are fixed [12]. To prevent such underestimation, the force stimuli should be applied to both cues. Otherwise, if force feedback to these two types of sensations cannot be realized for some reasons, the remaining cue is adjusted such that the perceived force would become equal to one with both cues intact, considering the contribution ratios of the two sensory channels.

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